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# Mass Outflows from Accretion Disks: Old and New Challenges

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**Abstract.** We summarize recent developments in modeling of mass outflows from accretion disks in AGN. We illustrate how the hydrodynamical and magnetohydrodynamical wind structures revealed in numerical simulations relate to observations. Important results from the numerical simulations include: no shielding from X-rays is needed to radiatively launch a wind from the inner disk; shielding is needed to accelerate the wind to high velocities. Disk winds launched magnetically seem to be too dense to be accelerated by line driving. It appears that we have an *all or nothing* situation for radiation-driving: radiation driving has to be responsible for both launching and accelerating the wind or a wind launched by some other mechanism must have a very finely tuned density in order to be accelerated by radiation driving to velocities as high as measured in BAL QSOs.

## 1. Introduction

Mass outflows in active galactic nuclei (AGN) are fairly common. Broad absorption lines (BALs) in QSOs are perhaps the most compelling evidence for such outflows. The BALs are always blueshifted relative to the emission-line rest frame,[1] indicating the presence of outflows from the active nucleus, with velocities in the ultraviolet as large as $66,000\ \mathrm{km\,s^{-1}}$. Other evidence for AGN outflows include narrow absorption lines (NALs). NALs observed in ultraviolet (UV) observations of some QSOs can be blueshifted by as much as $\sim\ 50,000$ km s$^{-1}$ (Hamann et al. 1997). NALs observed in UV observations of many Seyfert galaxies are blueshifted by several 100 km s$^{-1}$ (Crenshaw et al. 1999). NALs can also be due to highly ionized species such as those observed in a high-resolution X-ray observation of the Seyfert galaxy NGC 5548 obtained by *Chandra* (Kaastra et al. 2000). We refer a reader to Arav, Shlosman, & Weymann (1999); Crenshaw, Kraemer, & George (2002); and these proceedings for more details on observations of AGN outflows.

One of most plausible scenarios for AGN outflows is a wind from an accretion disk around a black hole. However, even if we agree that AGN outflows are indeed disk outflows, there are still many key questions that await answers. Here we mention just five: (i) From what radius on the disk do the outflows come?

[1] A few SDSS BAL quasars have a redshifted and a blueshifted component; see Hall et al. 2002.

(ii) Do the outflows need shielding from X-rays to avoid overionization? (iii) What is the mechanism responsible for launching the outflows from the disk? (iv) What is the mechanism responsible for accelerating the outflows to their terminal velocities? (v) All AGN are believed to have accretion disks, why then do not all AGN exhibit outflows?

Our goal here is to review various theoretical results and try to identify a physical disk wind model which is most promising in answering as many questions as possible concerning AGN flows with as few assumptions as possible.

Before we proceed, let us consider a specific question: is the terminal velocity of an outflow, $v_\infty$, a good indicator of the radius, $r_l$, from which the outflow was launched? One can argue that the answer to this question is positive if the terminal velocity is correlated with the escape velocity, $v_{esc}$, from the location where the flow was launched. Such a correlation between $v_\infty$ and $v_{esc}$ is one of the predictions of the radiation-driven wind theory (i.e., $v_\infty \approx$ a few $v_{esc}$, see Proga 1999 and references therein).

## 2. Hydrodynamical Models

Radiation pressure on spectral lines (line force) driving a wind from an accretion disk is the most promising hydrodynamical (HD) scenario for AGN outflows. Within the framework proposed by Murray et al. (1995) all five questions mentioned above can be addressed in one rather simple way: a wind is launched from the disk by the local disk radiation at radii where the disk radiation is mostly in the UV. Such a wind is continuous and requires shielding. The UV radiation emitted inside the wind launching region accelerates (radially) the wind. Consequently, the wind is equatorial and produces spectral features only for certain (high) inclination angles.

In Proga, Stone, & Kallman (2000, hereafter PSK), we attempted to model line-driven winds in AGNs within this framework. We applied line-driven stellar wind models (Castor, Abbott, & Klein 1975, hereafter CAK) to winds driven from accretion disks. We also took into account some of the effects of photoionization. In particular, we calculated the gas temperature assuming that the gas is optically thin to its own cooling radiation. In PSK, we took also into account the effects of photoionization on the line force by computing the parameters of the line force using a current value of the photoionization parameter, $\xi$, adopting results of Stevens & Kallman (1990, hereafter SK). SK's results show that the line force decreases sharply with increasing photoionization parameter.

In PSK, we found that a disk accreting onto a $10^8$ $M_\odot$ black hole at the rate of 1.8 $M_\odot$ $yr^{-1}$ can launch a wind at $r_l \sim 10^{16}$ cm from the central engine. The X-rays from the central object are significantly attenuated by the disk atmosphere so they cannot prevent the local disk radiation from pushing matter away from the disk. However, in the supersonic portion of the flow high above the disk, the X-rays can overionize the gas and decrease the wind terminal velocity. For a reasonable X-ray opacity, e.g., $\kappa_X = 40$ g$^{-1}$ cm$^2$, the disk wind can be accelerated by the central UV radiation to velocities of up to 15,000 km s$^{-1}$ at a distance of $\sim 10^{17}$ cm from the central engine. We note that this velocity agrees very well with the prediction of the standard CAK model for the wind terminal velocity (see e.g., Proga 1999). The covering factor of the disk wind is $\sim 0.2$. The wind

is unsteady and consists of an opaque, slow vertical flow near the disk that is bounded on the polar side by a high-velocity stream. A typical column density radially through the fast stream is a few $10^{23}$ cm$^{-2}$ so the stream is optically thin to the UV radiation. This low column density is precisely why gas can be accelerated to high velocities. The fast stream contributes nearly 100% to the total wind mass loss rate of 0.5 $\mathrm{M_\odot\,yr^{-1}}$.

In PSK, we took into account the attenuation of the X-ray radiation by computing the X-ray optical depth in the radial direction and assuming a simple formula for the $\kappa_{\mathrm{X}}$ dependence on the photoionization parameter. It remains to be seen whether fully self-consistent, multidimensional photoionization and dynamical calculations will confirm that a wind launched from a disk by the local UV disk radiation can shield itself from the X-rays in order to achieve velocities as high as those observed in AGN winds. Such photoionization calculations in connection with two-dimensional, time-dependent HD calculations are just starting to become feasible.

We emphasize that, within the framework of line driving, X-ray shielding is necessary for an observer to see AGN outflows in UV absorption lines and for the outflows to be accelerated. Assuming a steady state radial outflow and imposing total momentum conservation, one can show that unshielded gas outflowing with high velocities has too high a photoionization parameter to produce UV lines and to be driven by the line force. This result holds for an outflow consisting of a continuous wind as well as for an outflow consisting of dense clouds. The latter needs shielding from X-rays if the filling factor decreases with increasing radius — a requirement we do not know how to satisfy from first principles. A need for some shielding of clouds has been already hinted at in the literature (e.g., dKB).

To avoid overionization without shielding, the wind which is launched by a force other than the line force must be denser than the wind predicted by the line-driven wind models by several orders of magnitude. Thus if AGN outflows are unshielded and launched from an accretion disk at relatively large distances from the central object (where the local line force due to the disk is negligible) then we have to figure out not only what mechanism launches this dense outflow but also what mechanism accelerates the outflow to velocities much higher than the escape velocity from the location of the launch. Our conclusion that shielding of the wind from the X-rays is required regardless of the filling factor of the line-driven outflow is consistent with the observed anti-correlation for QSOs between the relative strength of the soft X-ray flux and the CIV absorption equivalent width (e.g., Brandt, Laor, & Wills 2000).

The above conclusions are based on assumptions more simplified than those adopted in our previous work (e.g., PSK, Proga & Kallman 2002). Nevertheless they are consistent with numerous simulations. Finally, we note that the wind terminal velocity sets an upper limit for the radius from which the wind is launched, provided the wind is line driven. The line-driven wind is more likely to achieve lower rather than much higher velocity compared to the escape velocity from the launching radius. The wind velocity can be lowered if the wind is overionized downstream as in PSK's simulations [see Proga (1999) for a discussion of when the wind terminal velocity can be lowered]. However, to accelerate radiatively a wind to velocities higher than $v_{esc}$, the wind density would have to

be significantly lower than the density of the line-driven wind, but this makes the wind very likely to be overionized and unable to be accelerated at all.

One of most appealing aspects of line-driven disk wind models is the fact that they predict from first principles outflows that are consistent with observations. Moreover, it is very encouraging that line-driven models, when applied to disk winds from cataclysmic variables, are not only consistent with observations but also are capable of reproducing them (e.g., Proga 2003b).

## 3. Magnetohydrodynamical Models

Magnetically driven winds from disks are the favored explanation for the outflows in many astrophysical environments (e.g., Blandford & Payne 1982; Uchida & Shibata 1985). Such winds do not require radiation pressure and thus can be important in low luminosity systems such as young stellar objects and systems where gas can be overionized by very strong radiation as in AGN. In the context of AGN outflows, magnetically driven wind models usually rely on the effects of magnetic fields as well as on line driving. For example, within the framework proposed by de Kool & Begelman (1995; see also Everett 2004, this volume) the five questions mentioned in Section 1 can be addressed in the following way: a wind is launched from an outer cold disk. Such a wind is made of dense clouds and does not require shielding. The wind is accelerated by the UV radiation emitted from the inner disk. The wind may be but does not have to be equatorial and can produce spectral features for all inclination angles provided there is at least one cloud in the line of sight.

At the moment it is still unclear whether a purely line-driven disk wind model or whether a hybrid model with magnetic and line-driving better explains observations. One may prefer the former simply because it does not invoke processes that cannot be modeled from first principles. In the latter case, one has to postulate a mechanism responsible for launching the clouds from the outer cold disks and a mechanism to confine the clouds so they will not be destroyed or overionized. However, this situation may change soon as new studies bring new insights into the physics of accretion disks and highly inhomogeneous magnetized flows.

For example, in Proga (2003a) we reported on numerical simulations of the two-dimensional, time-dependent magnetohydrodynamics (MHD) of line-driven winds from luminous accretion disks initially threaded by a purely axial magnetic field. We focused on a generic disk wind problem and did not include strong ionizing radiation. Such studies can help to understand AGN outflows because they address, for example, the problem of a wind produced outside a shielding, inner outflow.

In Proga (2003a) we used ideal MHD to compute the evolution of Keplerian disks, varying the magnetic field strength and the luminosity of the disk, the central accreting object, or both. We found that the magnetic field very quickly starts deviating from purely axial due to the magnetorotational instability. This leads to fast growth of the toroidal magnetic field as field lines wind up due to the disk rotation. As a result the toroidal field dominates over the poloidal field above the disk and the gradient of the former drives a slow and dense disk outflow, which conserves the specific angular momentum of the fluid. Depending

on the strength of the magnetic field relative to the system luminosity the disk wind can be radiation- or MHD-driven. The pure line-driven wind consists of a dense, slow outflow that is bounded on the polar side by a high-velocity stream. The mass-loss rate is mostly due to the fast stream. As the magnetic field strength increases first the slow part of the flow is affected, namely it becomes denser and slightly faster and begins to dominate the mass-loss rate. In very strong magnetic field or pure MHD cases, the wind consists of only a dense, slow outflow without the presence of the distinctive fast stream so typical of pure line-driven winds. Our simulations indicate that winds launched by the magnetic fields are likely to remain dominated by the fields downstream because of their relatively high densities. Line driving may not be able to change a dense MHD wind because the line force strongly decreases with increasing density.

## 4. Final Remarks

Recent numerical simulations in the HD limit as well as in the MHD limit reveal many important features of disk outflows. For example, no shielding is needed to radiatively launch a wind from the inner disk. Shielding is needed to accelerate the wind to high velocities. Disk winds launched magnetically seem to be too dense to be accelerated by line driving. It appears then that we have an *all or nothing* situation for line-driving: line driving has to be responsible for both launching and accelerating the wind; otherwise we require a rather fine tuning of the wind density so that some other mechanism produces an outflow with velocities as measured in BALQSOs. All of this is because the ionization balance is a key constraint on AGN outflows.

There are two groups modeling in great detail the ionization structure of AGN outflows: (i) Everett (2004, this volume) explores self-similar MHD disk wind models where an assumed steady state enables a detailed treatment of the photoionization and radiative transfer in one-dimensional approximation. (ii) Chelouche (2001; 2003) considered purely radiation-driven one-dimensional steady outflows. It is just a matter of time before multidimensional time-dependent simulations with sophisticated photoionization calculations will be applied to AGN outflows and we shall understand AGN outflows as well as winds in OB stars.

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## References

Abbott, D. C. 1982, ApJ, 259, 282

Arav N., Shlosman I., & Weymann. R. 1997, Mass Ejection from Active Galactic Nuclei, ASP Conference Proceedings, Vol. 128, (San Francisco: ASP)

Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883

Brandt, W. N., Laor, A., & Wills, B. J. 2000, ApJ, 528, 637

Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, ApJ, 195, 157 (CAK)

Chelouche, D., & Netzer, H. 2003, MNRAS, 344, 233

Chelouche, D., & Netzer, H. 2001, MNRAS, 326, 916

Crenshaw, D. M., Kraemer, S. B., Boggess, A., Maran, S. P., Mushotzky, R. F., & Wu, C. C. 1999, ApJ, 516, 750

Crenshaw, D. M., Kraemer, S. B. & George I. M. 2000, Mass Outflow in Active Galactic Nuclei: New Perspectives, ASP Conference Proceedings, Vol. 255, (San Francisco: ASP)

de Kool, M., & Begelman, M. C. 1995, ApJ, 455, 448 (dKB)

Hall, P. B., et al. 2002, ApJS, 141, 267

Hamann, F., Barlow, T. A., Cohen, R. D., Junkkarinen, V., & Burbidge, E. M. 1997, in Mass Ejection from Active Galactic Nuclei, ed. N. Arav, I. Shlosman, & R. Weymann, (San Francisco: ASP), 19

Kaastra, J. S., Mewe, R., Liedahl, D. A., Komossa, S. & Brinkman, A. C. 2000, A&A, 354, L83

Murray, N., Chiang, J., Grossman, S. A., & Voit, G. M. 1995, ApJ, 451, 498

Proga, D. 1999, MNRAS, 304, 938

Proga, D. 2003a, ApJ, 592, L9

Proga, D. 2003b, ApJ, 385, 406

Proga, D., & Kallman, T. R. 2002, ApJ, 565, 455

Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ, 543, 686 (PSK)

Stevens, I. R., & Kallman T.R. 1990, ApJ, 365, 321 (SK)

Uchida, Y., & Shibata, K. 1985, PASJ, 37, 515